Unraveling Long-Term Solar Variability and its Impact on Space Climate: *The Stars as Suns Project*

Dibyendu Nandy and P.C.H. Martens

Department of Physics, Montana State University, Bozeman, Montana 59717, USA

Abstract. It is well-known that solar variability influences the near-Earth Space environment at short timescales of days – an effect collectively termed as Space Weather. A lesser known and more subtle influence of solar variability at longer timescales, is however, just beginning to be appreciated. This long-term solar forcing, which is sometimes referred to as Space Climate, has important consequences for the formation and evolution of planetary atmospheres, evolution of life and global climate on Earth. Understanding the Sun's variability and its heliospheric influence at such scales stretching from millennia to stellar evolutionary timescales is therefore of fundamental importance and a much promising area of future research. However, our understanding of this variability, which is in part connected to the evolution of the solar magnetic dynamo, is limited by sunspot observations which exist only from early 17th Century onwards. In this paper I review the "Stars as Suns" project – in which we take a radically new approach to unraveling long-term solar variability through theoretical modeling and magnetic activity observations of Sun-like stars, which are at various evolutionary phases relative to the Sun.

Index Terms. Dynamo, Magnetism, Space Climate, Star, Sun.

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1. Introduction

The Sun influences our Space environment through its variable activity. While flares and coronal mass ejections originating in the Sun pose a serious hazard to satellites and telecommunications facilities on short timescales on the order of days, the solar radiative output affects (planetary and) global climate on much longer timescales from decennia to stellar evolutionary timescales (Lean 1997). The Sun radiates at different wavelengths; the total magnitude of this energy flux, its individual components (e.g., in visible, ultra-violet or X-ray), and the changes in them, have important consequences for the evolution of planetary atmospheres such as that of the Earth – including the synthesis of organic molecules and early life-forms.

The sources of both explosive solar phenomena and changing solar radiative output can be traced back to the presence of magnetic fields on the Sun. Understanding the origin and evolution of solar magnetic fields and its impact on our environment, therefore, is a fundamental and much promising area of solar-terrestrial research. Magnetic fields of stars – like the Sun – are generated in their interior by a hydromagnetic dynamo mechanism involving complex non-linear interactions between the magnetic fields and plasma flows (Parker 1955). While a complete description of this dynamo mechanism remains elusive, significant advances have been made recently in understanding certain aspects of it in the context of the Sun (See e.g., Nandy & Choudhuri 2002; Nandy 2003, 2004a; Charbonneau 2005). It is important to realize, however, that our current understanding of long term solar variability (and hence the long term behavior of the solar dynamo) is limited by the availability of long term sunspot data – continuous observations of which exist from only early 17th Century onwards. While records of the cosmogenic isotopes ^{10}Be and ^{14}C in ice cores and tree rings, respectively, have been used as tracers of solar activity going back a few thousand years (Beer et al. 1988; Stuiver & Braziunas 1993), it is not certain how reliably these empirical proxies indicate the actual solar variability – given that many other factors often contribute to the formation of these isotopes. However, these are the only means available right now for deciphering long term solar activity on the order of thousands of years.

Given this scenario, there is certainly a need for alternative approaches – motivated from a physical point of view – that can enhance our knowledge of solar activity from timescales of a few thousand years and stretching back to stellar and planetary evolutionary timescales on the order of billions of years. On the one hand, these alternative ideas can be used to test the reliability of current re-construction methods using cosmogenic isotopes. On the other hand, this knowledge will be an independent basis for understanding how the solar dynamo output evolved over the past with increasing age of the Sun. Thus it will throw light on how the Sun's variability shaped planetary atmospheres and the

Earth's global climate, clearly separating those due to anthropogenic forcing. Also, by extension, this knowledge can be used to predict solar variability at long time scales that may be relevant for future generations of humans and technologies in space.

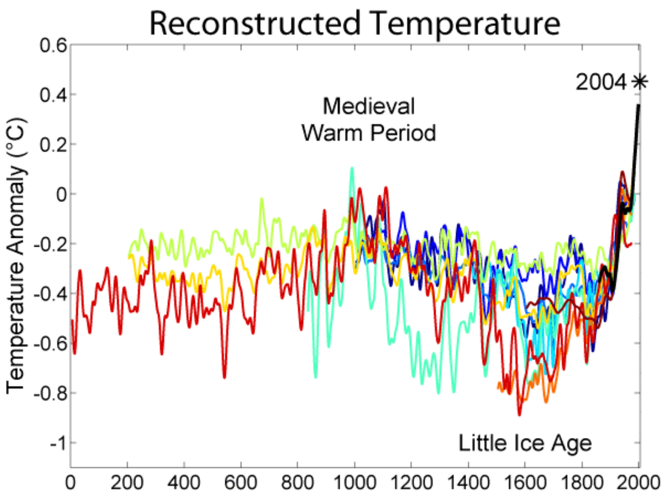

Fig. 1. Global temperature anomaly as reconstructed from various sources and by different researchers (colored curves) over the last two millennia. The black curve shows the instrumental record and the single point (star) depicts the annual mean for the year 2004 for comparison. Negative values signify cooler and positive values warmer temperatures, respectively. Major anomalies have been pointed out. The medieval warm period corresponded with a phase of apparently high (reconstructed) solar activity The Little Ice Age coincided with a documented period of low solar activity known as the Maunder minima. It is estimated that the significant warming in the last few decades may have a solar contribution of about 30%, the rest of it attributable to anthropogenic forcing mediated via human activities.

In this project we take a radically new approach to understanding long term solar variability – by recognizing that the Sun in its current state is but only one realization of the state of the evolution of the dynamo mechanism – the Sun's magnetic past and future equivalent to the activity of Sun-like stars in various evolutionary phases relative (i.e., younger and older) to the Sun. We seek to implement this approach by magnetic activity observations and magnetohydrodynamic (MHD) dynamo modeling of Sun-like stars in various phases of their evolution, such that we explore the dynamo parameter space spanning conditions that the Sun would have been in – in the past, and the Sun would be in – in the future.

In Section 2 we briefly describe what we mean by Space Climate and discuss evidence of solar forcing on the global climate. In Section 3 we lay down the physical basis for the Sun—Climate link and outline investigations of mechanisms that contribute to this link. In Section 4 we present some preliminary results from the "Stars as Suns" project whose aim is to reconstruct the magnetic variability of a Sun-like star as it ages. Finally we conclude in Section 5 with a discussion on the implications and cross-disciplinary applications of the envisaged research.

2. Space Climate and the Sun—Climate Link

The term "Space Climate" is relatively new and rather loosely defined and perhaps it is necessary here to elaborate on what we mean by it. The Sun's magnetic field and the solar wind that it spawns, governs the heliosphere – the sphere of influence of the Sun, within which sits the solar system. The variability of the Sun changes the magnetic and radiative environment within the heliosphere, including modulating energetic particle flux – effects of which are felt by planetary atmospheres and human technologies in Space. *The subject of Space Climate encompasses research on the changing electromagnetic and energetic particle environment within the heliosphere that is primarily governed by the Sun, it's forcing on planetary systems and the consequent response of the latter*. As opposed to Space Weather, Space Climate deals with relatively slower but long-term (decennia to billions of years) changes in the Sun and its effect on the solar system; it also includes those aspects of Global Climate change, e.g., synthesis of organic molecules and early life-forms that may be due to solar forcing.

Evidence of solar forcing at such long timescales primarily comes from its effect on Earth, which we are in a position to measure and document. This forcing is most likely to be similar across the solar system, although the magnitude of it and the response of individual planets would possibly be different. As far as our planetary habitat is concerned, numerous empirical relationships and statistical correlations exist between solar activity indicators and various components of global climate, including temperature, rainfall and indeed, major climatic events, some of which we discuss here (see also Fig. 1).

A documented phase of reduced solar activity between 1645 and 1715 A.D. known as the Maunder minima coincided with a period of long winters and global cooling on Earth (Eddy 1976; Hoyt & Schatten 1996). Solar forcing is also thought to be responsible for cyclic variations in climate and ecosystems during the Halocene (Hu et al. 2003). The 1470 year glacial climate cycle has also been associated with solar activity (Braun et al. 2005). Friis-Christensen & Lassen (1991) discovered a close relationship between solar cycle period (length) and land air temperature in the past century; connections have also been found between solar activity and sea surface temperatures (White et al. 1997). More recent studies indicate that the Sun could have contributed almost 30% to the global warming observed in the last few decades (Solanki & Krivova 2003; Scafetta & West 2005, 2006) – *the rest of it then attributable to anthropogenic forcing through greenhouse gas emissions*. Studies also link solar activity to cloud cover (Carslaw, Harrison & Kirkby 2002) and variations in rainfall, e.g., the Indian monsoon (Bhattacharyya & Narasimha 2005). Solar ultra-violet (UV) radiation also (destructively) affects the ozone layer in the upper atmosphere (McElroy & Salawitch 1989) – this layer is widely believed to play a determinant role in global climate. Indeed, more and more such relationships between solar activity and terrestrial climate indicators are emerging from diverse interdisciplinary studies, revealing a profound link between the Sun and Climate – possibly established with the formation of the solar system and the birth of Earth about 4.6 billion years ago. Of course one can argue that many of the empirical Sun-Climate relationships don't really mean anything and could have arisen due to factors unaccounted for. The unknown factors here could be many, and possibly important; we are talking about climate after all. *The goal of Space Climate research is then to critically examine the apparent Sun—Climate links and unambiguously determine to what extent the Sun and its variability is responsible and wherever possible, establish a clear physical basis for this forcing directly linking an effect on Earth to a cause originating in the Sun*. In the next section we examine this issue to a greater detail focusing on two different physical processes – both due to the changing magnetism of the Sun, which directly affects Earth in distinct ways via different climate parameters.

For more on Space Climate research, interested readers are referred to reviews by Lean (1997), de Jager (2005) and Versteegh (2005), the books "Solar Variability and its Effects on Climate" (Geophysical Monograph Series 2004), "The Sun, Solar Analogs and the Climate" (Springer 2005) and the topical issue of Solar Physics Journal (Mursula, Usokin & Cliver 2004) containing papers presented at the "First International Symposium on Space Climate" held at Oulu, Finland. One can also see http://en.wikipedia.org/wiki/Global_warming/ for a nice (although not reviewed) overview on Global Warming, its indicators and possible causes.

3. The Physical Basis of Solar Forcing on Climate – Total Solar Irradiance and Cosmic Ray Modulation

In this section we consider two physical ingredients that we believe lies at the heart of the Sun—Climate link. The first is the variation in the spectrally integrated total solar radiation – Total Solar Irradiance (TSI). The second is Cosmic Ray modulation by solar magnetic fields.

Magnetic fields on the solar photosphere contribute to TSI variations in and around the visible range of the electromagnetic spectrum, with other contributions coming from upper layers at higher energy solar radiation in UV, EUV and X-rays (due to magnetically mediated heating, reconnection or flaring events). The 11 year sunspot cycle modulates the number and distribution of sunspots seen on the solar surface. Although sunspots themselves suppress convective energy transport from beneath (due to their strong magnetic fields) therefore visibly appearing darker, the associated faculae, plage and overlying magnetic loops contribute significantly to an overall brightening – therefore the TSI correlates positively with the number of sunspots and varies in phase with it over the solar cycle (see Steiner & Ferriz-Mas 2005 for a related study). In Fig. 2 we plot the TSI variation over the last 3 sunspot cycles; the coupling between TSI and sunspot numbers is clearly evident.

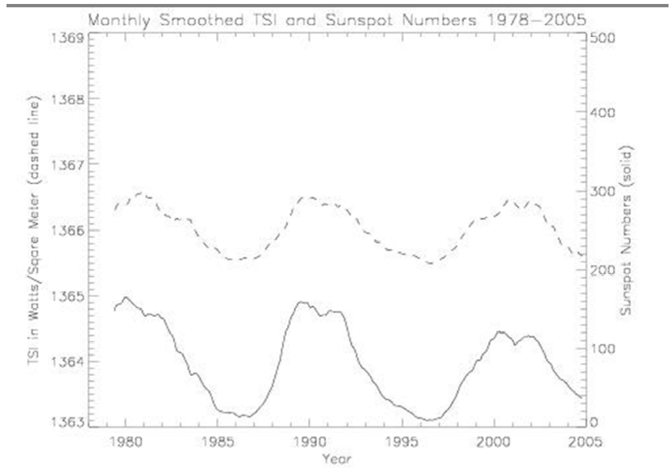

Fig. 2. The dashed curve shows the variation in TSI over time while the solid curve shows the solar cycle variation in the number of sunspots on the solar photosphere over the same period of time (monthly averages smoothed with a 13 month algorithm). The TSI variation is coupled to solar activity and varies in phase with it. The TSI data is courtesy the World Radiation Center (Davos) and the sunspot data is courtesy the Solar Influences Data Analysis Center (Belgium).

The primary energy input to the Earth's climate system is the total solar radiation quantified by TSI. Most of this energy is absorbed by the Earth's atmosphere and surface and some part of it is reflected back (most notably by clouds). This solar radiative energy input and its variations play a determinant role in governing the global temperature; reconstructed solar irradiance variations and global temperature data reflects this connection (see, e.g., Lean 1997; for a review on TSI variations see Frohlich 2000). Note that the extent and details of the TSI-temperature link is still a matter of active research. However, that this should be one of the major physical basis of solar forcing on the climate is beyond doubt – given the clear correlation between sunspot activity and TSI and the direct role of the latter in climate models.

The Sun's time-varying magnetic field also plays a crucial role in modulating the cosmic ray flux at Earth and this is the other major factor that plays a role in terrestrial climate. The periodic appearance, decay and spatiotemporal evolution of sunspot magnetic fields on the solar surface mediated via flux-transport processes (such as diffusion and meridional circulation) ultimately contribute to the large-scale solar dipolar and open flux (Solanki, Schüssler & Fligge 2000;

Wang, Lean & Sheeley 2005; Mackay & Lockwood 2002; Mackay & van Ballegooijen 2006). The open flux along with the solar wind spreads out across and beyond the solar system, defining the heliosphere. This magnetic field in the heliosphere traps incoming cosmic rays from galactic sources. When solar activity is higher, this is manifested in a correspondingly stronger magnetic flux in the heliosphere and therefore a lower cosmic ray flux at Earth. In Fig. 3 we plot the variation in the neutron flux (a measure of cosmic rays) at Earth over the last half-century along with the sunspot record over the same period of time. The anti-correlation between the two is clearly evident. Higher solar activity results in lower cosmic ray flux at Earth and vice-versa.

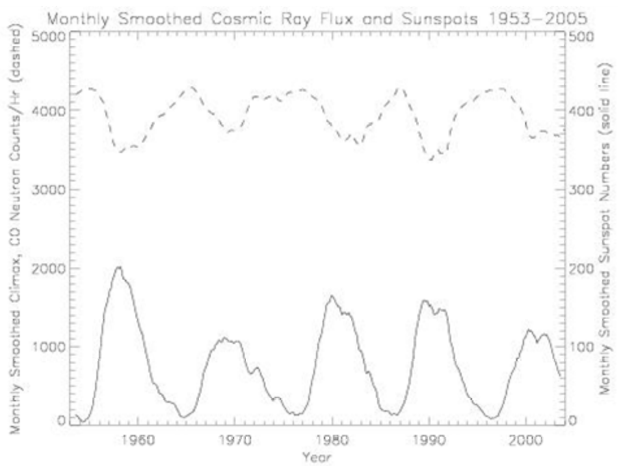

Fig. 3. The variation in the cosmic ray (neutron) flux (dashed line) and sunspot numbers (solid line) as observed over the last half-century. The anti-correlation between the two is clear. The smoothing algorithm is the same as in Fig. 2. The cosmic ray data is courtesy the CLIMAX Neutron Monitor (Colorado).

Cosmic rays ionize matter in the Earth's atmosphere and are therefore believed to play a role in seeding cloud formation (Svensmark 1998). Beyond just resulting in rainfall, cloud cover also reflects back incoming solar radiation (thereby reducing the actual energy used by the Earth system) and hence provides a means for controlling the global temperature. In summary then, the changing solar magnetic activity modulates cosmic rays and cloud cover – having consequences for Earth – the second possible physical link between the Sun—Climate system. We may point out here that the physical processes underlying modulation of cloud cover by cosmic rays is not well established yet and much more needs to be done to completely uncover the details.

4. The Solar—Stellar Connection: Reconstructing the Activity-Age Relationship of a Sun-like Star

We have discussed evidence linking the Sun's variability to Earth's climate and outlined the physical basis for this link. The Sun's effect, evident in our terrestrial habitat, is also expected to extend to other planets in the solar system. Although this Sun—Climate link has been scientifically explored in recent times and the evidence uncovered points to the link existing for at least a few millennia, it is very likely that this link was established with the formation of the solar system about 4.6 billion years ago. Some questions naturally arise then; what was the activity of the young Sun like; how did it evolve with age; how did this affect the evolution of planetary systems and the global climate; what is the future activity of the Sun going to be over its (main-sequence) lifetime and what does it imply for the ultimate fate of human beings? To answer these questions one needs to unravel past and future solar activity spanning a time of about 10 billion years. Given the inadequacy of current activity reconstruction techniques (using cosmogenic isotopes) to answer this, the only solution is to look at other Sun-like stars. By studying a sample of solar-like stars with a wide distribution of ages relative to the Sun (i.e., younger and older) and modeling and observing their magnetic activity, one can then reconstruct solar variability spanning billions of years across its main-sequence lifetime and subsequently use this (in conjunction with information about the luminosity variation) to understand its effect on Space Climate. This is precisely the aim of the "Stars as Suns" project.

To uncover the magnetic past and future of a solar-like star, one first needs to understand the magnetohydrodynamic (MHD) dynamo mechanism that is at the heart of stellar magnetic activity. Assuming axisymmetry, the magnetic field in spherical polar coordinates (as appropriate for stellar geometries) can be expressed as

$$B = B_\phi e_\phi + \nabla \times (A e_\phi).$$

The first term on the right hand side of the above equation is known as the toroidal component and the second term as the poloidal component of the magnetic field. The toroidal magnetic field is generated in stellar interiors by the stretching of the poloidal component by differential rotation (Parker, 1955). Due to their buoyancy, the strong toroidal flux tubes rise up radially from the base of the convection zone ultimately erupting through the surface as sunspots (or equivalently star-spots) of concentrated magnetic fields. The presence of rotation in stars generates Coriolis force and helical turbulent convection. The combined effect of this is the tilting and twisting of the rising magnetic fields to re-generate the poloidal field back (through a process known as the dynamo α-effect). This recycling of toroidal and poloidal components of the magnetic fields, feeding on the kinetic energy of the plasma motions within stellar interiors, keeps the dynamo going. There are of course many other details associated with the dynamo mechanism, including the role of diffusion and large scale circulation such as the meridional flow, but we do not get into those complexities here. Interested readers are referred to the reviews by Nandy (2004a) and Charbonneau (2005) for details on the dynamo mechanism.

The nature of the dynamo for a star – such as the Sun – is expected to evolve over the lifetime of the star with the evolution of the properties of its convection zone, primarily mediated through spin-down and angular momentum losses via stellar winds. This would result in a variation of the governing parameters and hence overall output, of the star's dynamo with time. A measure of the efficiency of the dynamo mechanism is the dynamo number (N_d) – the ratio of the source terms to the dissipative terms in the dynamo equations – which depends on various physical properties of the stellar convection zone. The dynamo generated magnetic activity is stronger for higher dynamo numbers and vice-versa. Another important parameter which describes the evolutionary state of stellar convection zones is the Rossby number (R_o) – which is the ratio of the star's rotation period to its convective-turn-around-time. It can be shown that $N_d \propto 1/\ R_o^2$ (for more details on these important dynamo parameters and the connection between them one can refer to Noyes, Weiss & Vaughan 1984 and Montesinos et al. 2001). Since the rotation period, depth of a star's convection zone and convective turn-over time evolves with stellar evolution – both N_d and R_o are expected to change over any given star's lifetime. As stars age their rotation period increases, with a corresponding increase in their Rossby number. Indeed, one might therefore expect the nature and output of the dynamo to change over the lifetime of any given star and this change to be similar for solar-like stars. Consequently, modeling of stellar magnetic activity (for efforts that are part of this project see e.g., Nandy 2004b; Wilmot-Smith et al. 2005) and observations of this activity in a varied sample of solar-like stars (at different main-sequence ages and with different rotation rates) can be used to gain insights on the temporal evolution of the solar dynamo mechanism.

Since the dynamo and Rossby numbers are coupled to the star's age and they are the primary determinant of dynamo action, it would be worthwhile to see how the stellar magnetic output varies theoretically with changing dynamo and Rossby numbers. In Fig. 4 we show a theoretically recovered variation in the amplitude and period of dynamo activity with these parameters from a reduced (with the removal of all spatial dependence) α-ω dynamo model (Wilmot-Smith et al. 2006) that includes time-delays to mimic the finite time required for flux transport between spatially segregated dynamo source regions (a situation that is expected in stellar interiors). The result from this general model which can, in principle, be applied to study activity in stars with different properties and spanning different dynamo parameters, shows that the amplitude of magnetic activity is strongly coupled to the dynamo number, increasing with higher dynamo numbers (equivalently decreasing with higher Rossby numbers since $N_d \propto 1/\ R_o^2$). This already provides a hint of how the dynamo activity should vary with stellar age – which we explore below.

We now turn to stellar observations. As a part of our ongoing efforts we are working on a sample of solar-like stars ranging in spectral class from F2 to K2 which have properties similar to that of the Sun and which have been observed in chromospheric Ca H+K (UV wavelength) and coronal X-ray emission – both indicators of stellar magnetic activity.

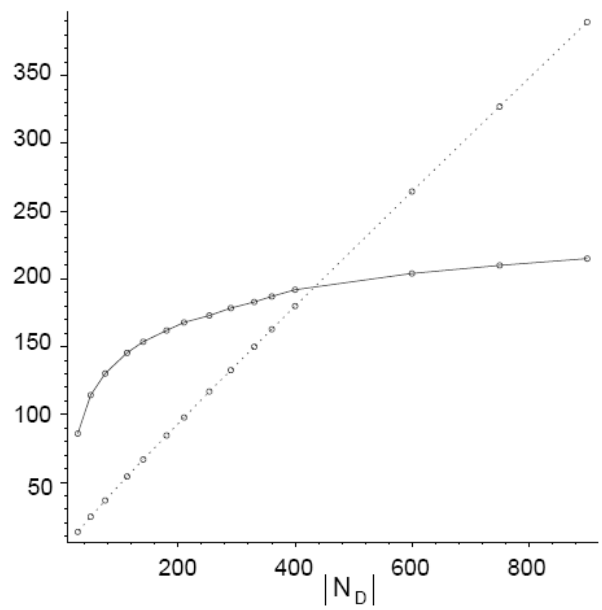

Fig. 4. Plotted is the variation in the amplitude (dashed line) and period (solid line) of dynamo activity with the magnitude of the dynamo number. The y-axis shows the value of the activity amplitude and period in arbitrary units while the x-axis, from left to right, shows increasing magnitudes of the dynamo number and correspondingly decreasing values of the Rossby number. This plot, from one of our solar and stellar dynamo models, shows the generic result that the amplitude of the dynamo activity increases with increasing dynamo number (and correspondingly, decreasing Rossby number).

The added constraint for building the stellar database is that the stars' rotation rates (or period) measurements should exist. Another important factor is that the stars should span a wide range in main-sequence ages so that the activity-age relationship can be established. For some of the stars the age has been determined by association with a cluster or by other means, while for some the age information doesn't exist. However it turns out that as stars age, they spin-down due to angular momentum losses via stellar winds and there is a clear relationship between the rotation period and age. We use those stars in our sample that have both the rotation period and age information to establish this empirical relationship (see Fig. 5). Following this we use the rotation period-age relationship to figure out the ages of those stars in our sample that did not have the ages pre-determined. Subsequently we use information about the rotation period and convective-turn-over-time (wherever available) to calculate the star's Rossby number and establish its relationship to age. Fig. 6 shows this relationship, namely that the Rossby number increases with age. Therefore, based on theoretical modeling as outlined earlier, one might expect the magnetic activity level to decline with age.

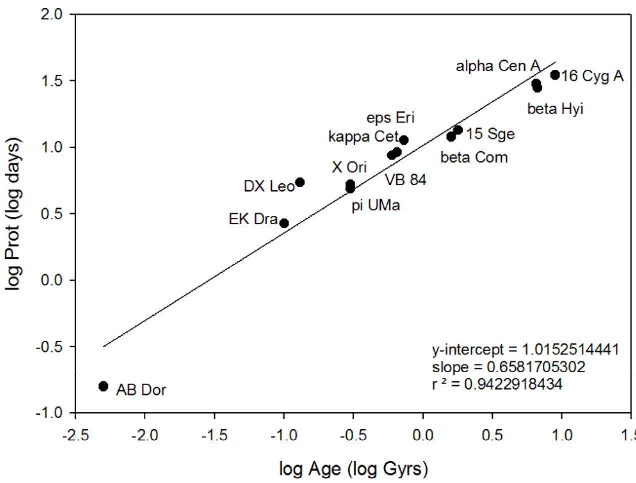

Fig. 5. The rotation rate—age relationship in a subset of our stellar sample in which the star's age could be pre-determined independently. The rotation period is plotted on the y-axis and the age on the x-axis (the plot is in log-base-10-scale).

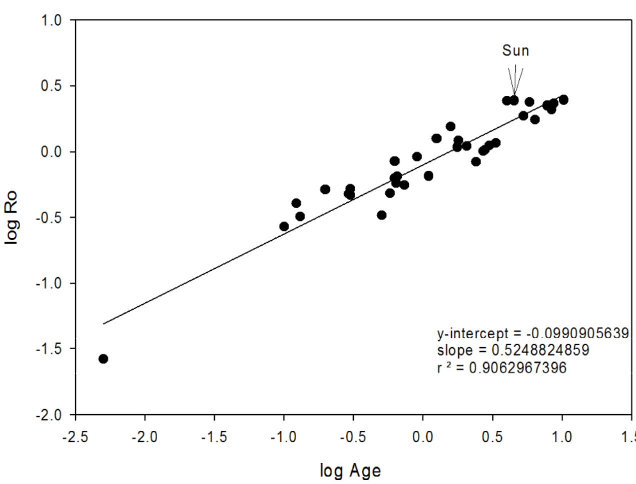

Fig. 6. The Rossby number (y-axis) —age (x-axis) relationship as recovered in our stellar sample. The scale is in log-base-10. The Rossby number R_o is seen to increase with the star's age. Since the dynamo number $N_d \propto 1/\ R_o^2$ and a decrease in the dynamo number results in less efficient dynamo amplification of magnetic fields, it is theoretically expected that the level or amplitude of dynamo generated magnetic activity will decrease with age.

The Mount Wilson project has compiled over 25 years of Ca H+K emission data from a wide variety of stars (Wilson 1978, Baliunas et al. 1983, 1985; Noyes et al. 1984; Saar & Brandenburg 1999), many of them solar-like. The chromospheric Ca H+K emission is a result of non-thermal heating associated with magnetic flux. Stellar coronal X-ray emission (due to magnetic heating of the corona) has also been observed in many solar-like stars (see e.g., Hempelmann, Schmitt & Stepien 1996; Messina & Guinan 2002; Micela & Marino 2003; Gudel 2004).

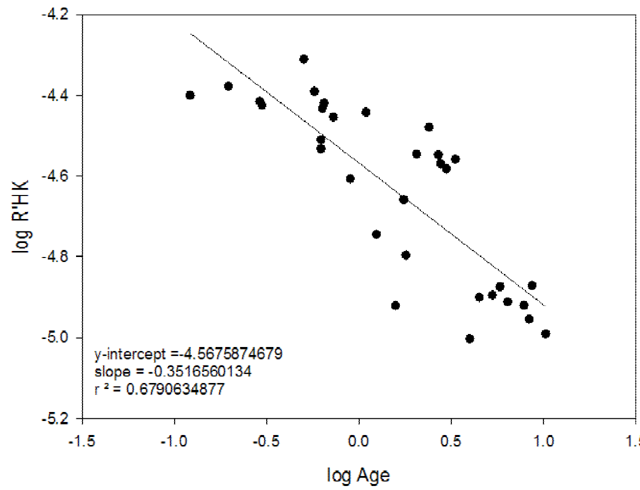

Fig. 7. Plotted here is the age dependence of chromospheric Ca H+K flux in our sample of stars. On the y-axis is a particular measure of the Ca H+K flux (attributed to magnetic activity) and on the x-axis is age (in log-base-10 scale). The data for the chromospheric emission has been compiled from various published sources related to the Mount Wilson project. The level of magnetically mediated chromospheric emission clearly decreases with age.

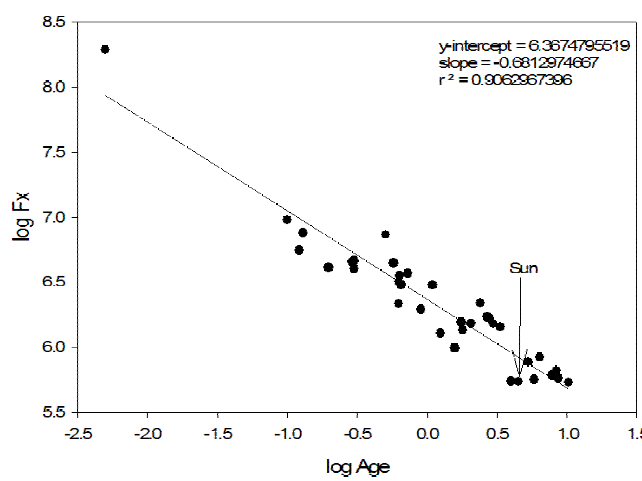

Fig. 8. The age (x-axis) dependence of the stellar coronal X-ray flux (y-axis) is shown here (in log-base-10 scale). The stellar X-ray flux has been compiled from various published sources utilizing data from ROSAT, XMM-Newton and other X-ray surveys. The stellar coronal X-ray emission is seen to decrease with age, the dependence if more pronounced and tighter, indicating that X-rays may be a more useful tool for such investigations.

We associate the Ca H+K and X-ray flux from stars in our sample with their age and pooling them together, reconstruct the variation in the emission levels with age. The results recovered (Fig. 7 and Fig. 8), clearly shows that the magnetic activity of a Sun-like star declines over its main-sequence lifetime of about 10 billion years.

5. Discussions

We have presented here preliminary results from the "Stars as Suns" project. The project was originally envisaged to explore solar-stellar connections – the aim being to better understand the solar dynamo mechanism by confronting it with the wider (dynamo) parameter space available from stellar observations; a secondary aim was to study the evolution of the solar dynamo with time. From our related efforts and independent work by others, however, a significant new direction of research has emerged.

The wider implication of the evolution of the solar dynamo mechanism in the context of Space Climate research has become evident in recent times and so have the scope and relevance of the "Stars as Suns" project become substantially larger and important.

Beyond its connection with just the global temperature as suggested by the geological record, the changing Sun and its changing radiation over the past billions of years could have played a crucial role in the modulation of the climate system of the early "young" Earth and in the evolution of primitive life-forms in planetary atmospheres. For example, the "young" Sun's higher EUV radiation or lower luminosity could have affected the synthesis of amino acids and nucleic acids; thus a quantitative estimate of the early Earth's radiation environment is crucial for discriminating between competing theories for the origin of life, e.g., the cold incubator versus the hot primordial soup. Conversely, solar radiation could have played a negative role in the destruction of life-forms on planets lacking a protective magnetosphere. Also, for the long term planning of the ultimate fate and future direction of humans and other living organisms on Earth and the associated technologies, one needs to have an idea of how solar activity will change in the distant future. Indeed, the stakes for unraveling long-term solar variability, and its impact on Space Climate, are high.

Our focus is to illuminate this relatively unexplored role played by solar forcing in shaping planetary climate and habitat by uncovering the long-term evolution of the Sun's activity. In our studies we have exploited the Solar-Stellar connection; there is much to be learned from the stars. On the one hand we are studying the theoretical aspects of solar and stellar magnetic field generation and its evolution with stellar age through dynamo modeling. On the other hand, we are complementing this by observational analysis of stellar luminosity and magnetic activity data. This dataset is not complete, and indeed sparse. In this context, a targeted space mission to study the magnetic activity of a wide sample of solar-like stars, which are relatively younger and older to the Sun, in various wavelengths would be extremely timely and important. Given that many generations of human beings hardly cover any notable fraction of the evolutionary lifetime of a star, only in such a study lies any significant hope for the reconstruction of very long-term solar activity.

Acknowledgments. The "Stars as Suns" project was originally envisaged by the authors (D.N. and P.C.H.M.) of this paper. However, the preliminary results reported here also involve significant contributions from many students. These include Antonia Wilmot-Smith, Sarah Lakatos and Jenna Rettenmeyer. The stellar magnetic activity data used here has been assimilated from diverse published sources and projects and we acknowledge those contributions that are in the public domain, including scientific journals. We are also thankful to Loren Acton, John Priscu and Duncan Mackay for useful conversations on various aspects of our work. Finally, we gratefully acknowledge NASA's *Living With a Star* Program for funding this project through grant NNG05GE47G.

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